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in Nuclear Materials Identification System (NMIS)
Resulting From a DT Neutron Generator**

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MONTE CARLO EVALUATION OF THE IMPROVEMENTS IN NUCLEAR MATERIALS IDENTIFICATION SYSTEM (NMIS) RESULTING FROM A DT NEUTRON GENERATOR

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ABSTRACT

Nuclear safeguards active measurements that rely on the time correlation between fast neutrons and gamma rays from the same fission are a promising technique. Previous studies have shown the feasibility of this method, in conjunction with the use of artificial neural networks, to estimate the mass and enrichment of fissile samples enclosed in special, sealed containers. This paper evaluates the use of the associated particle sealed tube neutron generator (APSTNG) as the interrogation source in correlation measurements. The results show that its use is of particular importance when floor reflections are present. The Nuclear Materials Identification System (NMIS) presently uses ^{252}Cf ionization chambers as interrogation sources for the time-dependent coincidence measurements. Because triggers from this source are associated with neutrons emitted in any direction, adjacent materials such as the floor and nearby containers could affect the measurements and should be accounted for. Conversely, the APSTNG, together with an alpha particle detector, defines a cone of neutrons that can be aimed at the item under verification, thus removing the effects of nearby materials from the time-dependent coincidence distributions. Monte Carlo calculations were performed using MCNP-POLIMI, a modified version of the standard MCNP code. The code attempts to calculate more correctly quantities that depend on the second moment of the neutron and gamma distributions. The simulations quantified the sensitivity enhancements and removal of the effects of nearby materials by substituting the traditional ^{252}Cf source with the APSTNG.

INTRODUCTION

This paper evaluates the associated-particle sealed tube neutron generator (APSTNG) as the interrogation source in the source-driven noise analysis method for the assay of nuclear materials. In the Nuclear Materials Identification System (NMIS) developed at Oak Ridge National Laboratory, the time-dependent cross-correlation between a timed neutron source and detector response is one of the signatures acquired [1]. Previous studies and measurements have demonstrated the sensitivity of this and other related signatures to fissile mass when Cf^{252} is used as the interrogating source [2-4].

The purpose of this paper is to compare the sensitivity of the APSTNG source to a Cf^{252} source for the assay of uranium metal castings. To this end, a set of MCNP-POLIMI Monte Carlo simulations were performed to obtain source-detector covariance functions for two sources: (1) a Cf^{252} source in an ionization chamber and (2) an associated particle sealed tube neutron generator of 14.1 MeV neutrons. The APSTNG, currently in development at ORNL, will detect a cone of alpha particles from the DT reactions. Because the 14.1 MeV neutrons are emitted in the opposite direction from the alpha particle, a cone of neutrons will be defined and aimed at the fissile

material. A recent report [5] pointed out the advantages associated with the APSTNG timed source of neutrons: it is directional, can be turned off, and emits only one neutron per deuterium-tritium reaction event, so all multiple events come from induced fissions. The high-energy neutrons are more penetrating of shielded containers. Moreover, all neutrons have the same velocity: the transmitted neutrons arrive at the detectors at a known time and the less energetic fission neutrons arrive at the detectors at later times.

The Monte Carlo simulation of correlation measurements that rely on the detection of fast neutrons and photons from fission requires that particle interactions in each history be described as closely as possible. The MCNP-POLIMI code [6] was developed from the standard MCNP code to simulate each neutron-nucleus interaction as closely as possible. In particular, neutron interaction and photon production are made correlated and correct neutron and photon fission multiplicities have been implemented. At each collision, relevant information on neutron and gamma collisions is recorded, for example reaction type, target nucleus, energy deposited, and position. A post-processing code analyses the collision data and calculates the correlation functions. This code can be tailored to model specific detector characteristics. These features make MCNP-POLIMI a versatile tool to simulate particle interactions and detection processes.

The paper is organized as follows: the simulation geometry is given in Section 2; Section 3 briefly describes the MCNP-POLIMI output file; finally, the results of the simulations performed with Cf^{252} and APSTNG sources to interrogate uranium castings of different enrichments are given in Section 4.

SIMULATION GEOMETRY

We performed MCNP-POLIMI simulations for the standard uranium metal castings for storage at the Oak Ridge Y-12 plant, as shown in Figure 1. In this configuration, the interrogating source was placed on one side of the item to be inspected, and four fast plastic scintillation detectors were positioned on the opposite side. The total mass of the uranium metal casting was 18.5 kg, approximately. The enrichment of the casting was set to 93 wt% U^{235} and 0.2 wt% U^{235} (the two enrichments will be referred to as ‘enriched’ and ‘depleted’). The detectors, cubes of side 7.62 cm, were placed one on top of the other in a 2x2 array. The distance between the source and the casting, x_s and the distance between the detectors and the castings, x_d , were set to 41.7 and 35.5 cm, respectively. The separation between the fissile sample and the measurement apparatus allows the positioning of a container for the sample.

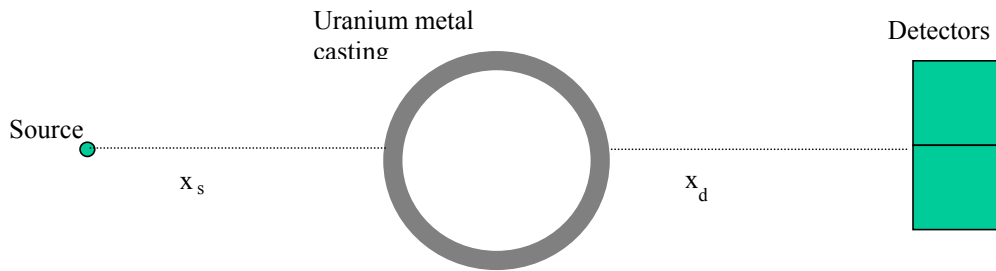


Figure 1. Top view of the geometry used in the MCNP-POLIMI simulations. x_s and x_d are the source-to-casting and detector-to-casting distances, respectively.

The simulations were repeated for geometries with and without a concrete floor (Oak Ridge concrete, with sand replaced by crystal limestone, having density 2.3 g/cc), placed at a distance of 60 cm from the bottom of the uranium casting, and having a thickness of 20 cm.

MCNP-POLIMI OUTPUT FILE

The MCNP-POLIMI output file consists in a detailed account of particle interactions inside the detectors. In particular, the output file reports information on each energy deposition by neutrons and photons interacting with the detectors. An excerpt of this data file is shown in Table 1. Consider, as an example, history number 16 (first three rows of Table 1). The particle number is 97 for the three rows, indicating that the same neutron (projectile type 1) interacted via elastic scattering (interaction type -99) with hydrogen (target nucleus 1001) in detector number 2 (cell number of collision event). This neutron deposited approximately 531 keV in the first interaction, 55 keV in the second, and 1 keV in the third, as shown in column 7 of Table 1. The time in shakes (10^{-8} sec) at which the interactions took place is given in column 8 of Table 1. Time is measured after the originating source event. The column labeled ‘generation number’ tells us that this neutron originated by induced fission inside the uranium sample: it is a particle of the third generation of fissions. Generation zero particles are source particles, or particles generated in the interactions of source particles with nuclei by all interactions except for nuclear fission.

Table 1. Excerpt of MCNP-POLIMI output for uranium casting interrogated by APSTNG source.

History number	Particle number	Projectile type*	Interaction type ^Δ	Target nucleus*	Cell number of collision event	Energy deposited in collision (MeV)	Time (shakes)	Collision Position (x, y, z)			WGT	Generation number	Number scatterings	Code
...														
16	97	1	-99	1001	2	0.5309	8.095	43.57	4.88	1.84	1	3	5	0
16	97	1	-99	1001	2	0.0553	8.395	44.29	5.57	1.85	1	3	6	0
16	97	1	-99	1001	2	0.0014	11.722	44.92	5.04	3.78	1	3	9	0
109	1	1	0	6000	5	8.398	1.798	43.98	-7.52	6.31	1	0	0	0
132	1	1	-99	1001	5	13.9313	1.778	42.06	-2.98	1.42	1	0	2	0
132	1	1	-99	1001	5	0.1036	2.075	42.55	-2.34	2.88	1	0	3	0
132	1	1	-99	1001	5	0.0281	2.264	42.25	-2.39	3.44	1	0	4	0
132	1	1	-99	1001	5	0.0131	2.372	42.16	-2.22	3.63	1	0	5	0
335	58	1	-99	6000	4	0.0019	3.72	43.98	0.16	9.54	1	3	5	0
335	58	1	-99	1001	3	0.0042	4.069	42.64	-0.01	9.13	1	3	6	0
485	1	1	-99	1001	5	8.2582	1.872	48.08	-2.19	7.51	1	0	1	0
495	24	2	1	6	2	0.1461	1.036	43.87	3.46	5.06	1	1	2	0
495	24	2	1	6	2	1.2823	1.036	43.95	3.47	5.08	1	1	3	-1
495	24	2	1	6	2	0.038	1.038	43.41	3.8	5.12	1	1	4	-1
495	24	2	1	1	2	0.0793	1.038	43.28	3.76	5.08	1	1	5	-1
495	24	2	1	6	2	0.0421	1.042	43.69	3.19	5.93	1	1	6	-1

* 1 = neutron; 2 = photon

Δ -99 = elastic scattering; 1 = Compton scattering

• 1001 = hydrogen; 6000 and 6 = carbon

The data collected in the output file is post-processed using a code that takes into account the physical properties of the plastic scintillating detectors [6]. In particular, we consider the light output generated by the interactions of neutrons and photons with the hydrogen and carbon atoms of the detector, and the pulse generation time (time during which light pulses are added together to generate a single impulse). The code calculates the source-detector covariance functions on the basis of the sequence of counts in the single detectors.

SIMULATION RESULTS

Figures 2 and 3 show the source-detectors covariance function acquired in the interrogation of depleted and enriched uranium metal castings using Cf^{252} and APSTNG interrogating sources. The signature was subdivided into the neutron contribution (Figure 2) and the photon contribution (Figure 3) (note the difference in the scales of the two figures). The results show that the signature acquired using the Cf^{252} source is only weakly sensitive to sample enrichment, the differences being evident only for the neutron part and for time delays greater than 60 ns. Conversely, the signatures acquired using the APSTNG source show sensitivity to sample enrichment. In the neutron part of the signature, the differences are evident for time delays greater than 24 ns.

Further simulations showed that when considering the difference between the neutron signatures acquired for the enriched and depleted samples, there is a factor of ten more coincident counts when the APSTNG source is used in place of Cf^{252} .

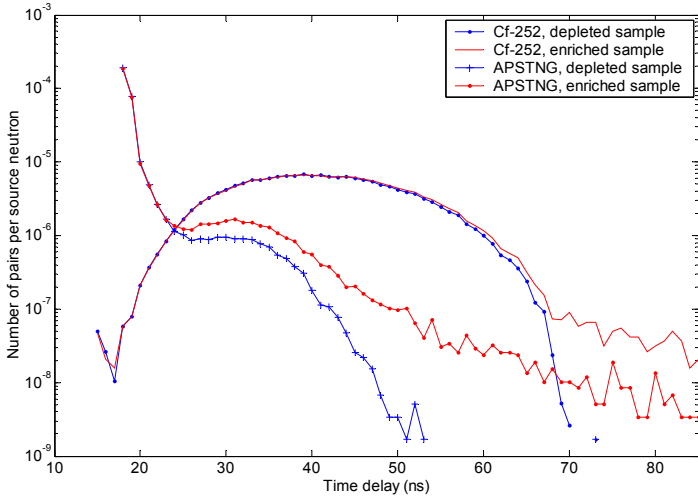


Figure 2. MCNP-POLIMI simulation of source-detector covariance functions for uranium metal castings of different enrichments, interrogated by Cf^{252} and APSTNG source (neutrons only).

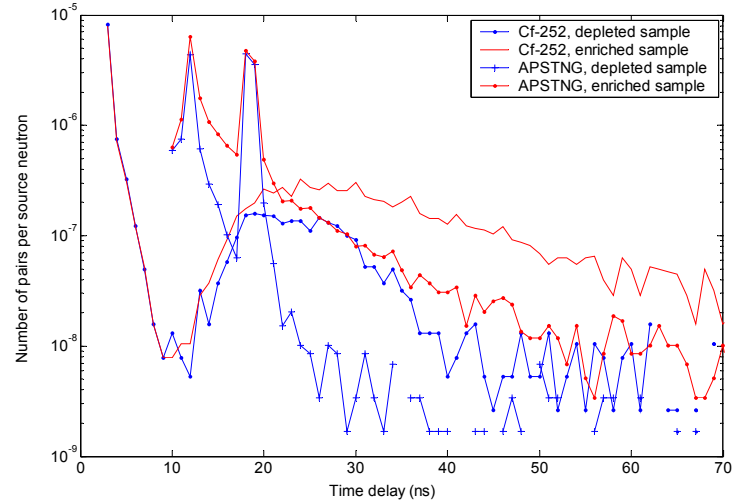


Figure 3. MCNP-POLIMI simulation of source-detector covariance functions for uranium metal castings of different enrichments, interrogated by Cf^{252} and APSTNG source (photons only).

Figures 4 and 5 show the breakdown of the total simulated signature into two components: generation zero particles and particles from induced fission. Generation zero particles are particles coming to the detector from the source, or generated in the interactions of source particles with nuclei by all interactions except for nuclear fission. Gamma rays generated by inelastic scattering of source neutrons are a typical example of generation zero particles. The source component in the case of Cf^{252} is given by gamma rays, arriving on the detectors at a time lag of approximately 3 ns, and by a broader distribution due to neutrons arriving on the detectors at time lags between 20 and 70 ns (Figure 4).

Figure 5 shows the result in the case of the APSTNG source. The 14.1 MeV neutrons arrive on the detectors at time delay equal to approximately 18 ns (second sharp peak of Figure 5). The first peak, centered at a time delay of approximately 12 ns, is given by gamma rays generated inside the fissile sample by inelastic scattering or induced fission.

Neutrons and gamma rays generated by induced fission comprise the second component of the signature. Figure 4 shows that in the case of Cf^{252} , the signal given by induced fission is more than one order of magnitude lower than the signal coming from the source. This is true for both depleted and enriched samples.

Figure 5 shows that in the case of the APSTNG source, the signal given by induced fission is prevalent for time delays greater than 25 ns. This is true for both depleted and enriched samples. However, the effect is prevalent in the case of the enriched sample, showing the sensitivity of this signature to fissile mass.

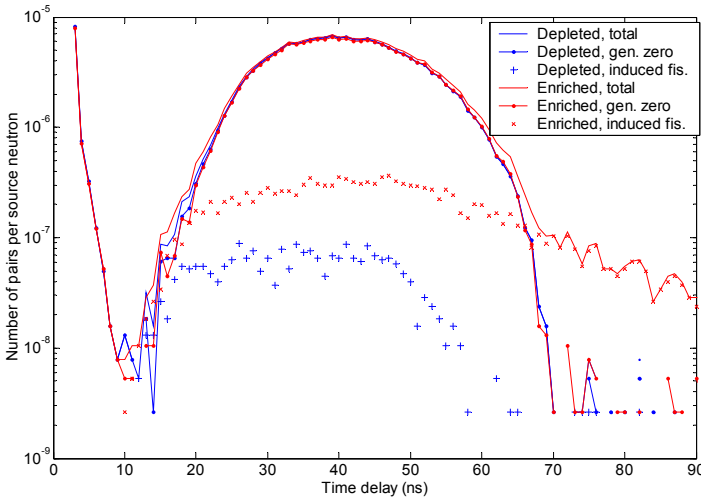


Figure 4. MCNP-POLIMI simulation of source-detector covariance functions for uranium metal castings of different enrichments interrogated by a Cf^{252} source. Total signature is subdivided into generation zero particles and induced fission particles.

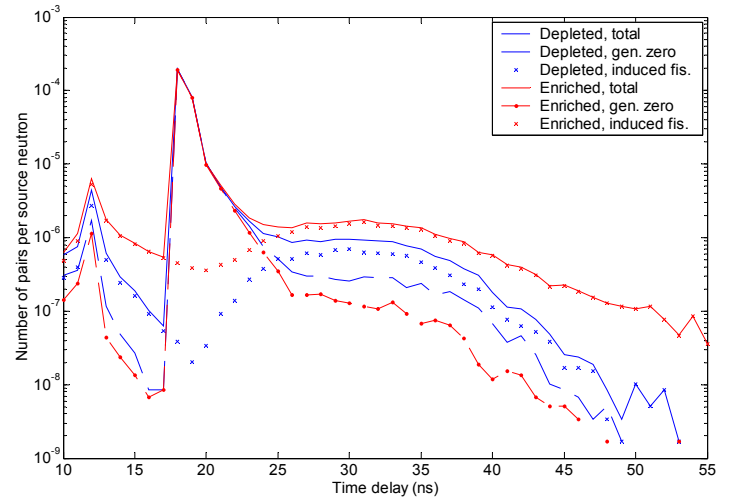


Figure 5. MCNP-POLIMI simulation of source-detector covariance functions for uranium metal castings of different enrichments interrogated by the APSTNG source. Total signature is subdivided into generation zero particles and induced fission particles.

Figures 6 and 7 show the percentage of the total signature given by induced fission, for both Cf^{252} and the APSTNG source, as a function of the time delay (ns).

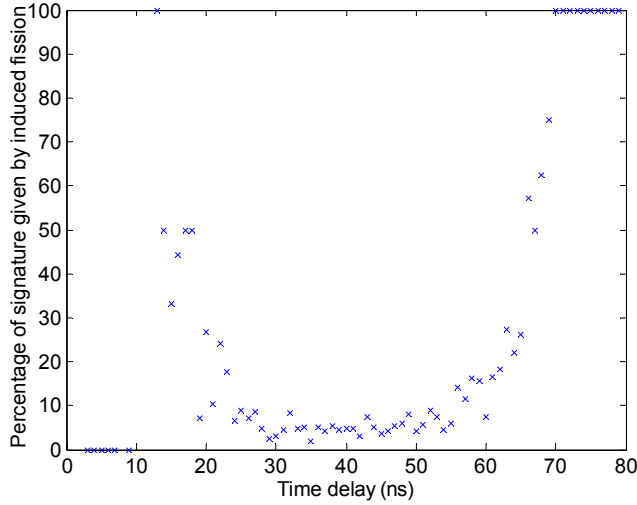


Figure 6. Percentage of source-detector covariance signature given by induced fission for enriched casting, as a function of time delay: Cf^{252} source.

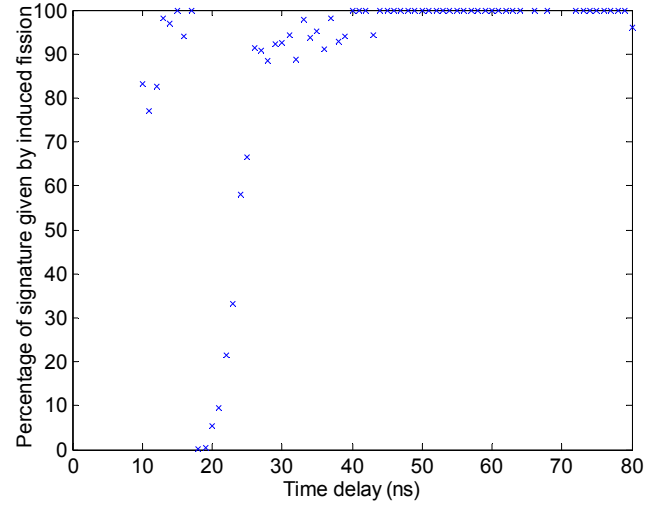


Figure 7. Percentage of source-detector covariance signature given by induced fission for enriched casting as a function of time delay: APSTNG source.

Figures 8 and 9 show the MCNP-POLIMI simulations performed to take into account the concrete floor. As it can be seen, in the case of the Cf^{252} source the floor reflection of neutrons and gamma rays is evident (Figure 8). There is a second gamma peak, occurring approximately 4 ns after the first, which is due to the gamma rays from the source that are scattered by the floor and reflected towards the detector. The effect is negligible in the rising edge of the neutron peak and on the peak itself. The scattered neutrons are evident after approximately 65 ns from the source fission.

Figure 9 shows the simulations for the APSTNG source. In this case the source neutrons are emitted in a cone aimed at the fissile sample, and the floor effect is negligible throughout the acquired signature.

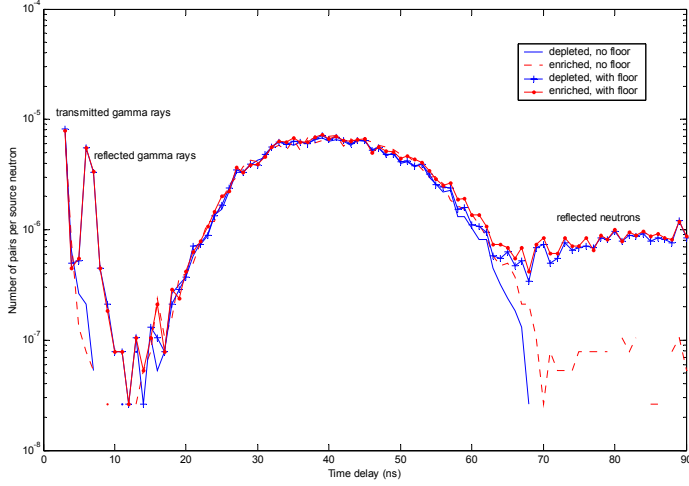


Figure 8. Evaluation of the floor effect for Cf^{252} source.

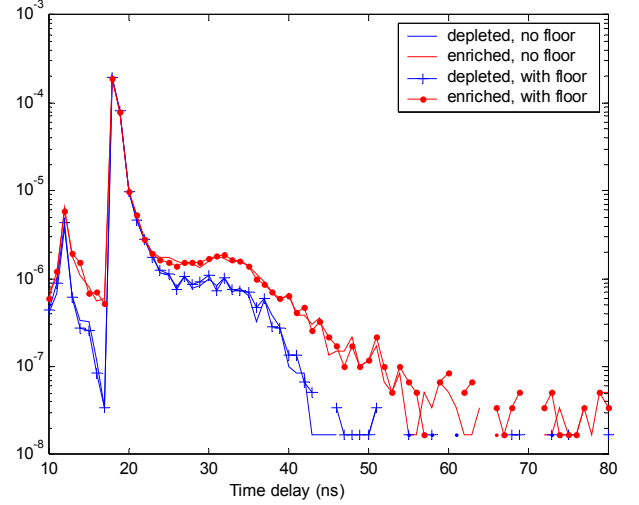


Figure 9. Evaluation of the floor effect for APSTNG source.

CONCLUSIONS

In this paper, we used the Monte Carlo code MCNP-POLIMI to compare the Cf^{252} and associated particle sealed tube neutron generator (APSTNG) as interrogation sources in active measurements based on fast correlation measurement of neutrons and gamma rays from induced fission. The signature acquired using the APSTNG is more sensitive to fissile mass. By use of a feature of the Monte Carlo code, it was shown that great part of the signature acquired using the APSTNG is given by induced fission inside the sample. This is not true in the case of the Cf^{252} source.

Because the APSTNG emits neutrons inside a cone aimed at the fissile sample, the acquired signature is not influenced by floor reflections.

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